Multimode Interference (MMI) coupler based All Optical Switch: Design, Applications & Performance Analysis

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***Abstract*---This paper reviews the basic of multimode interference (MMI) coupler and its application in optics, especially for optical switching. We have demonstrated the design & performance of 2 x 2 MMI coupler based all optical switch of lesser dimensions than conventional structures. This structure is based on special multimode region shape, which leads switch to have less coupling loss & lesser cross talk. The variations of the refractive indices of various sections to achieve switching actions are kept in the range of 1-2%. In later part, the proposed switch is used for design & analysis of higher order switches (4x4 & 8x8 switches) using Banyan, Benus and Spanky- Benus architectures.**

***Index term*--- All optical switches, multimode interference (MMI) coupler, self imaging, large switch architectures.**

I. Introduction

Multimode interference (MMI) structures have found wide application as low-order couplers, splitters, combiners, switches and multiplexers. In principle, the MMI devices can be used as switch by eliminating optical confinement to change the wave guide behaviors or by altering the imaging length by changes in refractive index of the MMI couplers [1]. Recent advances in MMI devices have led to design of ultra-short MMI couplers, segmented MMI structures and cascaded MMI switches [2]. The tapering of MMI structure could also be useful in designing various devices and proven as alternative with reduced beat length to design devices based on MMI structures [3]. Tapered MMI coupler have shown reduction in device geometry as, ref. [4] reported the 4 x 4 parabolically tapered MMI coupler with minimum uniformity of 0.36 dB and excess loss of 3.7 dB.

Various optoelectronic materials with MMI & other structures have been used as substrate to design all optical switches like Si, SOI, InP, InP/InGaAsP, InGaAs–AlGaInAs, LiNbO3, photonic crystals etc. InP/lnGaAsP optical integrated MMI switches [5] and InGaAsP-InP MZI optical space switch [6] are some of examples. All-optical switches (O-O-O) do not require optoelectronic conversion and regeneration steps and shows a significant advantage where high bandwidth is needed and slow routing is acceptable, but at the same time they are being relatively slow and insensitive as compared to mixed switches (O-E-O).

II. All Optical Switches

Theoretically, an all optical switch (O-O-O) is independent of bit rate and protocols with unlimited scalability, which can lead the network more flexible in nature. The choice of technology, switch architectures and size as well, plays an important role in designing of all optical switches with minimum fabrication losses. The figure 1 shows a basic all optical switch with two different possible switching states named as bar & cross state. In this, inputs & outputs are in optical form and the switching is also done in optical form with in the device. The device said to be in 3db state (50:50 state) when the power at input port is divided equally at output ports.

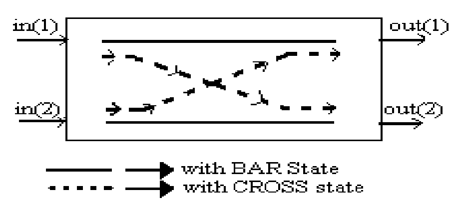

Figure 1. All optical switch

The use of all optical switches are now taking over the use of O-E-O switches, as the later switches requires complex circuitry and have their own limitation while performing switching smoothly &

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lossless. Yet the use of all optical switches are to cover up O-E-O switches uses in optical switching because of their difficulty in accommodating within the circuit with use of VLSI technology, while fabrication with low fabric losses and to use the same to design high order switches to be used with other applications.

III. Self Imaging in Multimode Waveguides

As explained in [7], imaging is achieved in MMI coupler when input field is reproduced in single or multiple images at periodic intervals along a multimode waveguide [8].

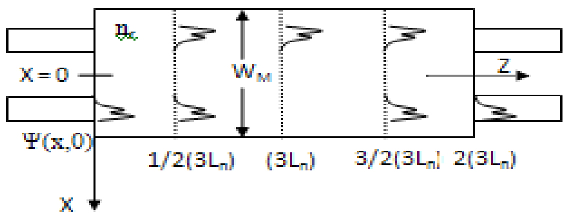

Figure 2. Field pattern in 2×2 MMI coupler, ref. [8].

The input field profile $\Psi(x, 0)$ imposed at z=0 and totally contained within W_M , including guided and radiative modes (fig.1) is estimated [8] as:

$$\Psi(x,0) = \sum_{v} (c_v \psi_v(x))$$

Where ψ_v is the normalized modal field distribution of the v'th mode. c_v, the field excitation coefficient and $\Psi(x,L)$, the field profile at distance z=L are given as [8]

$$c_v = \frac{\int \Psi(x,0)(\psi_v(x))\,dx}{\sqrt{\int \psi_v^2(x)dx}}$$

$$\Psi(x,L) = \sum_{v=0}^{m-1} (\psi_v(x) c_v) \exp\left[j \frac{v(v+2)\pi}{3L_\pi} L\right]$$

The field profile at $\Psi(x, L)$ is basically a reproduction of the given input field at x=0 ($\Psi(x, 0)$). As suggested and explained by Soldano [8] and Ulrich [9], the field profile at the input ($\Psi(x, 0)$) is replicated at regular intervals producing single and multiple mirror images according to the following conditions [10]

For single images:

$L = p\,(3L_\pi)$ with p = 0, 1, 2.

& for multiple images:

$L = p/2\,(3L_\pi)$ with p = 1, 3, 5.

The use of these images (single and multiple) in cross, bar and 3db couplers are depicted as follows:

- When $L = 2p\,(3L_\pi)$, the field reproduced at L is in phase with the field at the entrance, and the coupler is in bar state.
- When $L = (2p + 1)\,(3L_\pi)$, the field reproduced at L is in antiphase with the input field, and the coupler is in cross state.
- When $L = (p + 1/2)\,(3L_\pi)$, the field is linear combination of input field and its mirror image in yz plane, hence in 3db state.

IV. MMI All Optical Switches

A. Design of 2×2 MMI Optical Switch

In multimode interference coupler, switching can be achieved by varying the refractive index of the material in the coupling region using various methods like heating electrodes or by current conjunction. Figure 1 illustrates the different parts of proposed design of 2×2 MMI coupler based optical switch [11]. The physical properties of the material in the coupling region have been varied in order to get switching action. Fig.1 is the X-Z slice cut on the wafer of the waveguide. The switch is about 800µm long and 11µm wide in size. The wafer is having the same refractive index as that of cladding i.e. 1.49. The 3D wafer properties include clad (refractive index =1.49) as material and substrate with thickness equal to 15 µm. The device has been designed using optiBPM layout designer.

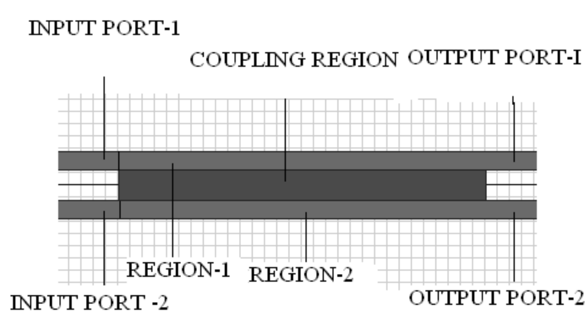

Figure 3. MMI coupler based 2×2 switch [11].

Dimensions and refractive indices of the different regions of the MMI coupler to set different states (cross, bar and 3-dB state) are shown in table I and II respectively.

TABLE I.
MMI COUPLER DIMENSIONS

Regions	Length (µm)	Width (µm)
Input port	100	3
Region 1	700	3
Region 2	700	3
Coupling region	600	3

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TABLE II.
REFRACTIVE INDEX OF MMI COUPLER REGIONS

State	Refrac. index of region 1	Refrac. index of region 2	Refrac. index of coupling region
Bar	1.791	1.791	1.740
Cross	1.791	1.791	1.791
3-dB	1.791	1.791	1.797

The input plane has been selected with MODE as the starting field and 0.0 as the Z-offset and global data is set with refractive index as modal and wavelength at 1.55µm. TM polarization and 20 mesh points are used to calculate 2D isotropic simulation at scheme parameter of 0.5, propagation step of 1.55and TBC as the boundary condition. Figure 4, 5 and 6 shows simulation result of MMI coupler in different states using BPM simulator.

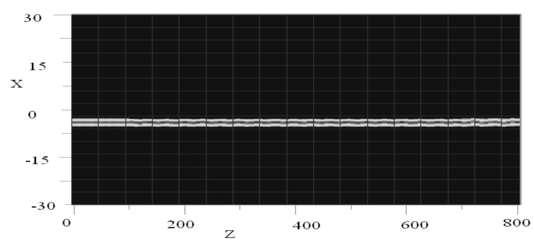

Figure 4. 2D view of output in bar state.

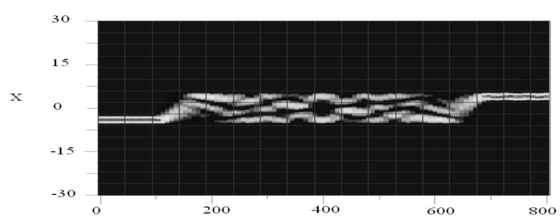

Figure 5. 2D view of output in cross state.

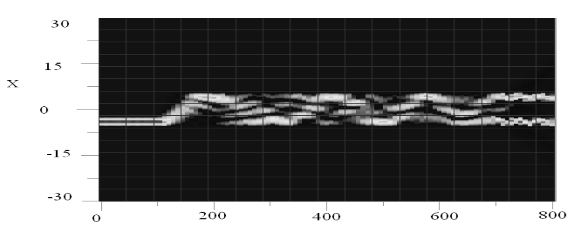

Figure 6. 2D view of output in 3dB coupler state.

B. Design of 4×4 Banyan MMI optical switch

In a banyan network the number of switching elements in each path is fixed and equal to $\log_2 N$. The 4×4 banyan optical switch consist of four 2×2 proposed switch [10] as shown in figure 7. To check the switch performance, continuous wave (CW) laser inputs of single frequency of 193.5THz with different power levels are used. The proposed switch performance found to best at 1.55µm wavelength (f =193.5THz.) to couple maximum power through the switch. For the proposed switch (Fig. 7.) the coupling loss in the cross & bar state was measured as 2.75%, and 5.38% respectively. The crosstalk comes out to be 6.99 $\times 10^{-05}$, which is negligible. The Powers in the input ports of the continuous wave (CW) laser and the corresponding output powers are tabulated in table-III.

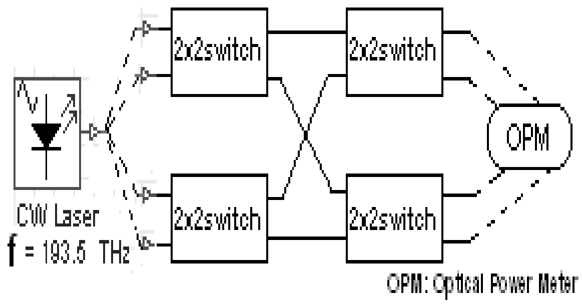

Figure 7. Banyan network based 4×4 switch

TABLE III.
INPUT & OUTPUT POWERS

Port No.	Input power (mW)	Output power (mW)
1	50	49.72
2	100	96.54
3	150	146.3
4	200	192.6

C. Performance analyses of 8x8 switch with different architectures.

The proposed MMI basic switching element is used with different architectures (Banyan. Benus & Spanky-Benus) to design 8x8 switch. To check the performance of 8x8 switch using said architectures, continuous wave (CW) laser inputs of single frequency of 193.5THz with different input powers are used. All 2×2 proposed switches are in cross state of switching. In 8×8 switch, the total numbers of basic switching elements (MMI 2x2 switches) required are 12, 20, and 28 for Banyan, Benus & Spanke-Benes architecture respectively, as shown in fig. 8, 9 and 10. In a banyan network the number of switching elements in each path is fixed and equal to $\log_2 N$ and there is a unique path between an input and an output port [12]. These characteristics have made banyan networks attractive for constructing optical switching networks based on direction couplers, because losses and attenuation of an optical signal are proportional to the number of couplers that the optical signal crosses.

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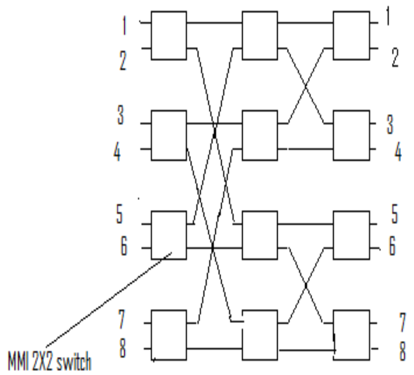

Figure 8. Banyan 8×8 switch, ref. [12]

The vertically stacked Banyan network [13] is used to overcome the blocking issues faced by the architecture. The resulting interconnections have nonblocking characteristic, while neither increasing the number of stages nor sacrificing the loss uniformity property originally possessed by the Banyan network structures [13].

Benes is efficient rearrangeably nonblocking architecture to build larger switches [14]. An N×N Benes switch required $(N/2)(2\log_2 N\text{-}1)$ 2×2 switches, with N being a power of two [11]. Figure 9 shows 8×8 Benes switch network using basic 2×2 switches.

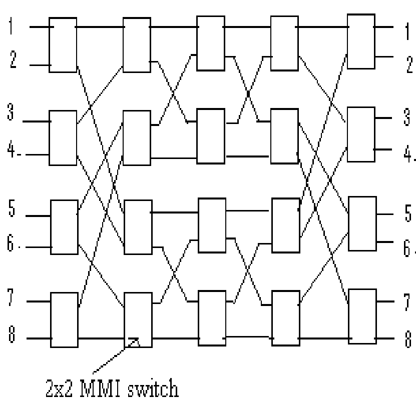

Figure 9. Benes 8x8 switch, ref. [12]

The loss in Benus network is the same through every path in the switch because each path goes through $2\log_2 N\text{-}1$, 2×2 switches [12]. Its two main drawbacks are that it is not wide sense nonblocking and that a number of wave guide crossovers are required, making it difficult to fabricate it in integrated optics [12]. Also the switches with greater port counts may possess some idle ports.

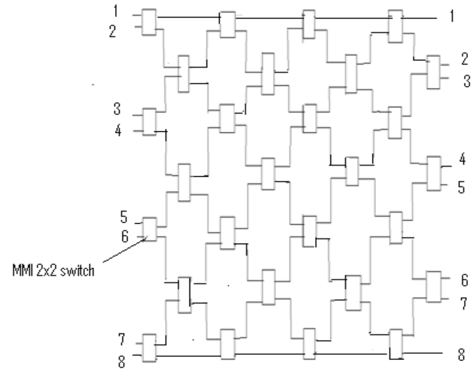

Figure 10. Spanke-Benes 8x8 switch, ref. [12]

Spanky-Benus architecture (figure 10) or n- stage planar architecture is rearrangeably nonblocking and requires N (N-1)/2 switches, with shortest path length N/2 and the longest path length N [13]. There are no crossovers. Lack of wide sense non blocking character & uniformity in internal path losses are major problems with this architecture.

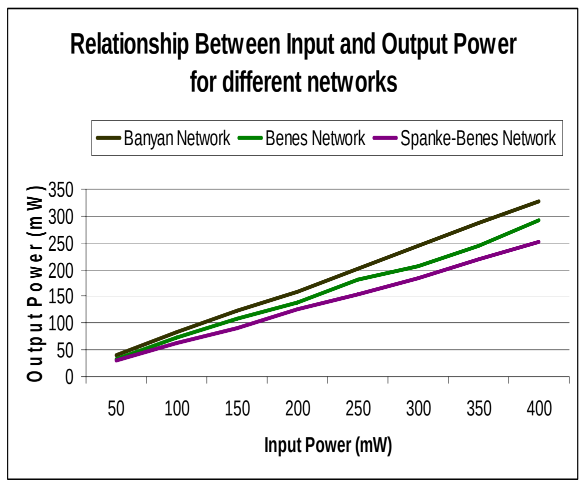

Figure 11. Performance analysis for 8x8 switch

Figure 11 shows the 8x8 switch performance, when designed & simulated for different power levels at various input ports applied at a time using architectures discussed above. The graph clearly indicates that the losses are proportionally increasing with respect to the total no. of switching elements required and the number of cross level within a specific architecture. In graph the uppermost line is showing performance of the switch within banyan network & the middle one is related with the Benes architecture. The input power levels are in the range of 50mW to 400mW. With assuming all other conditions ideal, the switch response is most promising with the Banyan followed by Benes and Spanky-Benes respectively.

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CONCLUSIONS

We have demonstrated a 2×2 MMI optical switch with extremely low crosstalk and negligible coupling loss (6.99×10^{-05}). The large switches designs, 4x4 & 8x8 switch using various architectures with the proposed basic MMI based switching element are elaborated. We have also discussed that how we can convert a blocking Banyan switch in to a nonblocking switch. Without using SOAs, Proposed 4×4 Banyan architecture optical switch showing a very less coupling loss. In design of 8x8 switch with discussed architectures, Banyan configuration is showing best result as compare to others architectures. There is further scope of producing the better results using semiconductor amplifiers (SOA's) in these networks. The SOA's can be used within the structure as intermediate elements or at last before producing the outputs.

REFERENCES

[1] M. P. Earnshaw, D. W. E. Allsopp "Semiconductor space switches based on MMI couplers" *Journal of Lightwave Technology*, page no. 643-650, vol. 20, no. 4, April 2002.

[2] Laurence Cahill "The modeling of MMI devices" ICTON 2006, page no. 138-141, *ieeexplorer*, 1-4244-0236-0/06.

[3] P. P. Sahu "A tapered structure for compact multimode interference coupler "*IEEE Photonics Technology Letters*, Vol. 20, NO. 8, April 15, 2008, page no, 638-640.

[4] Hongzhen Wei, Jinzhong Yu, Zhongli Liu, Xiaofeng Zhang, Wei Shi, and Changshui Fang "Fabrication of 4 x 4 tapered MMI coupler with large cross section" *IEEE Photonics Technology Letters*, Vol. 13, No. 5, May 2001.

[5] Shintaro Niwal, Shinji Matsuo,Takaaki Kakitsuka, Kenichi Kitayama "Experimental demonstration of 1x4 InP/lnGaAsP optical integrated multimode interference waveguide switch" *20th International Conference on Indium Phosphide and Related Materials*, IPRM 2008, 25-29 May 2008, Page(s):1– 4.

[6] N. Agrawal, C. M. Weinert, H.4. Ehrke, G. G. Mekonnen, D. Franke, C. Bornholdt, and R. Langenhorst "Fast 2 x 2 Mach-Zehnder optical space switches using InGaAsP-InP multiquantum- well structures" *IEEE Photonics technology letters*, Vol. 7, No. 6, June 1995, page no. 644-645.

[7] Singh, Ghanshyam, Singh, Anoop, Yadav, R.P., Janyani, Vijay "Design and analysis of low loss MMI based 4×4 optical switch using Benes architecture with SOAs", *IEEE PhotonicsGlobal@Singapore, 2008.*ieeexplorer.com:10.1109/IPGC, 2008.4781478., page(s):1 – 4.

[8] L.B.Soldano,. and E.C.M Pennings, "Optical multimode interference devices based on self-imaging: Principles and applications," *J Light wave Tech*., vol. 13, no. 4, pp. 615-627, 1995.

[9] R. Ulrich and G. Ankele, "Self imaging in homogenous planar waveguides," *Appl. Phys. Lett*., vol. 27, no. 6, pp. 337-339, NY 1975.

[10] Singh, Ghanshyam, Singh, Anoop, Yadav, R.P., Janyani, Vijay ""Design and analysis of low loss MMI based 4×4 optical switch using Benes architecture with SOAs" ICOCN, PhotonicsGlobal@Singapore, 2008. IEEE 8-11 December, 2008. 0.1109/IPGC.2008.4781478., Page(s):1 – 4.

[11] Singh, Ghanshyam, Sharma, M.K., Yadav, R.P., Janyani, Vijay "Design of 4×4 banyan optical switch using MMI switches with low crosstalk & low coupling loss" *International Conference on Recent Advances in Microwave Theory and Applications. 2008,*, 10.1109/AMTA,2008. 4763225, page(s):416 – 418.

[12] Georgios I. Papadimitriou, Chrisoula Papazoglou, and Andreas S. Pomportsis, "Optical Switching" *Wiley series in microwave & optical engineering*, Wiley Interscience, ISBN: 0-471-68596-8 (2007).

[13] X.Jiang, P.H.Ho, and S. Horiguchi," Performance Modeling for All-Optical Photonic Switches Based on the Vertical Stacking of Banyan Network Structures," *IEEE Journal on Selected Areas in Communications*, 23, 2005, pp: 1620-1631.

[14] A.jajszcyk, "Optimal structures for Benes switching networks," *IEEE Transactions on communications*, 27, 1979, pp: 433-437.

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